LOWELL OBSERVATORY
MARS HILL ROAD, 1400 WEST
FLAGSTAFF, ARIZONA 86001

FINAL TECHNICAL REPORT

OCCULTATION STUDIES OF THE SOLAR SYSTEM

NASA GRANT NSG-7603
1 July 1979 through 30 November 1989

Principal Investigator: Robert L. Millis

Co-Investigators: Lawrence H. Wasserman
Edward Bowell
Otto G. Franz

Lowell Observatory
1400 West Mars Hill Road
Flagstaff, Arizona 86001

INTRODUCTION

For nearly ten and one-half years, NSG–7603 provided the basic support for a program of solar system research at Lowell Observatory based on observation of occultations. This wide-ranging program included design and construction of specialized instrumentation for observation and prediction of occultations, development of techniques for identifying and precisely predicting upcoming occultations, observation of occultations from permanent observatories and from remote sites around the world, and analysis of a variety of types of occultation data. Among the more important scientific accomplishments resulting from this program are: (1) direct measurement of size and shape for Ceres, Pallas, Juno, and seven other asteroids, (2) firm proof of the existence of an atmosphere on Pluto, (3) measurement of the mass ratio of Pluto and Charon, and (4) development of improved constraints of the geometries of the Uranian Rings and Neptune's ring arcs.

INSTRUMENTATION

In the course of this grant, three portable occultation observing systems were designed and built. Each system consists of a 14-inch telescope, a two-channel photoelectric photometer, and a high-speed data-recording system. These systems have been used successfully throughout the life of this grant to observe occultations in the field at sites as distant as northeastern Australia and central Mexico. Additionally, the photometers and data systems have been used for occultation observations on permanent telescopes in the United States, New Zealand, Australia, and the Canary Islands. We take pride in the durability and scientific productivity of this Lowell Observatory-designed instrumentation.

Also during the grant, a new 18-inch astrograph was developed at Lowell. This instrument was constructed at low cost using government surplus optics and an existing telescope

mount at the Observatory. Construction of the astrograph was funded by a grant from the Perkin Foundation and by the private resources of the Lowell Observatory. NSG-7603, however, was the primary beneficiary of the instrument. Since commissioning in 1985, this telescope has been used effectively to refine predictions of asteroid occultations.

PREDICTIONS

Efficient techniques for identifying future occultations of stars by solar system objects have been developed under this grant. From comparatively primitive beginnings restricted to the *SAO Star Catalog* and a quite limited set of asteroids, we have devised software for computerized searches of upcoming asteroid occultations. Our predictions are now published for two-year intervals, with the most recent search spanning a composite catalog of 326,000 stars and complete for all numbered asteroids. We also publish predictions for occultations by planets and selected satellites.

In addition to the catalog searches, we have performed limited searches based on photographic plates taken either with our astrograph, the U. S. Naval Observatory 61-inch telescope, or the Lick Double Astrograph. The most productive of these was the joint Lowell–USNO–Lick program which resulted in the accurate prediction for the occultation of P8 by Pluto on 9 June 1988.

ASTEROID OCCULTATIONS

While a wide variety of different types of occultations have been observed under this grant, it is fair to say that we have chosen to emphasize prediction and observation of occultations of stars by asteroids. During the grant we have observed ten such events, including those involving Ceres, Pallas, and Juno. Accurate diameters and shapes derived from these occultations have provided the basis for recalibration of the standard radiometric model. Hence, much of the information we have on sizes of small solar system bodies is ultimately based on the results from NSG-7603.

Two of the three asteroids whose masses are well known (Ceres and Pallas) are among those whose sizes we have measured. Consequently, we have been able to derive the bulk densities of these two bodies. An occultation by the third such asteroid, Vesta, was observed a year ago under the follow-on grant to NSG-7603. All three asteroids have densities typical of rocky material, although Vesta is somewhat more dense than the other two.

Another result of the successful observation of so many asteroid occultations has been a realization of the scarcity of minor planet satellites. While such postulated objects were in vogue at the beginning of this grant, the continued failure to detect them in subsequent occultations has dampened the earlier enthusiasm.

A list of the asteroid occultations which we have successfully observed under this grant is given in Table I.

TABLE I. Asteroid Occultations Observed Under NSG-7603

Date	Event	Reference
11 Dec 79	AG+0°1022 by Juno	Millis *et al.* 1981
7 Oct 81	SAO 187124 by Thisbe	Millis *et al.* 1983
15 Nov 82	AG+39°303 by Ursula	Millis *et al.* 1984
22 Nov 82	AG+29°398 by Minerva	Millis *et al.* 1985
26 Apr 83	BD+21°1797 by Europa	Unpublished
29 May 83	1 Vulpeculae by Pallas	Dunham *et al.* 1983
16 Sep 84	SAO 14599 by glaja	Millis *et al.* 1989
13 Nov 84	BD+8°471 by Ceres	Millis *et al.* 1987
11 Apr 85	AG+20°1138 by Antigone	Unpublished
8 Dec 87	AG+40°783 by Bamberga	Millis *et al.* 1989

PLUTO OCCULTATION

The most challenging occultation for which predictions have been seriously attempted was the 9 June 1988 occultation of P8 by Pluto. We developed a strategy whereby a standard field containing Pluto and P8 was photographed repeatedly over a period of weeks using the USNO 61-inch Astrometric Reflector. A dense secondary reference net for this field was provided by Arnold Klemola based on plates taken with the Lick Double Astrograph. The USNO plates were measured at Lowell on the PDS microdensitometer and a predicted ground track calculated by Lawrence Wasserman. When one remembers that the angular diameter of Pluto is 0.11 arcsec and the semi-amplitude of its barocentric motion induced by Charon is 0.13 arcsec, it is evident how difficult this prediction was. Figure 1 shows the predicted ground track compared with that actually observed.

The occultation was actually observed at the eight sites marked in the figure. We observed from one of these—Charters Towers—with one of our three portable systems. The resulting lightcurve (Figure 2) showed that an extended atmosphere is present and that the atmosphere contains either a haze layer or a steep thermal gradient. Analyses of these observations are continuing.

A byproduct of the Pluto prediction effort has been an estimate of the Pluto–Charon mass ratio. Evidence of Pluto's barycentric motion is clearly evident in the USNO/Lowell astrometry. Our initial interpretation of these data suggests that the Pluto–Charon mass ratio is significantly less than 7—the value expected if the two bodies have equal densities and the radii derived from the mutual events. Therefore, either Pluto is less dense than Charon or Pluto is smaller than previously believed. Moreover, our results are not consistent with the assumption, adopted in the mutual event analysis, that only Pluto varies in brightness with rotational phase.

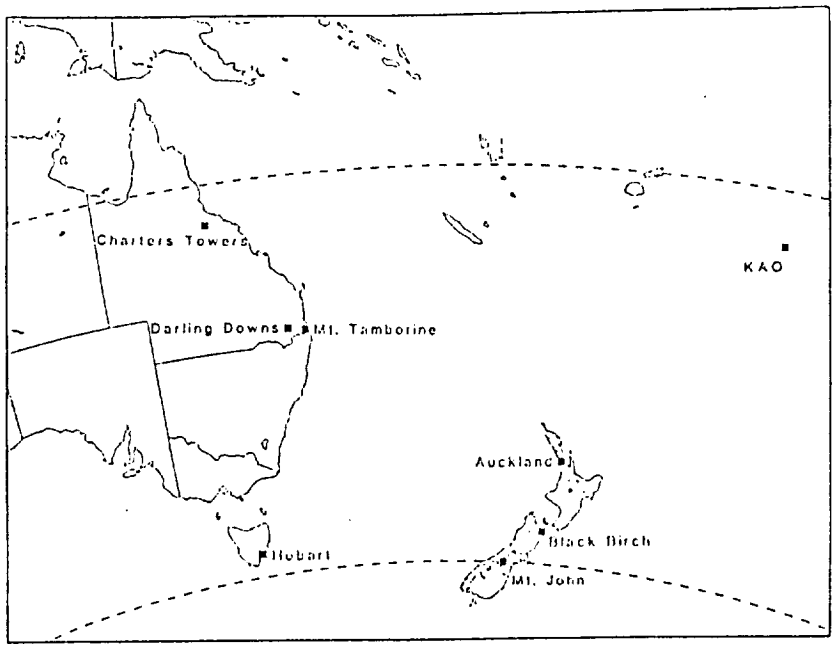

Figure 1. The observed ground track of the 9 June 1988 occultation of P8 by Pluto. Filled squares mark the eight sites where the occultation was observed. The dashed lines are at the distance from the center of the track where the star light was reduced to 76% of its unocculted level.

OTHER OCCULTATIONS

In addition to asteroid occultations and the occultation by Pluto, we have observed several other types of events. In particular, we observed the 22 April 1982 occultation by Uranus and the Rings from the British 1.5-meter telescope in the Canary Islands. We also have observed two close appulses involving Neptune which helped place limits on the extent and opacity of the ring arcs. Finally, in 1979 and 1985/86 we recorded over 100 Galilean Satellite mutual event lightcurves. These data were used by Kaare Aksnes and Fred Franklin to significantly improve the orbits of the satellites.

REVIEW PAPERS

At the beginning of this grant, Millis co-authored (with J. L. Elliot) a review of the asteroid occultation field for the classic volume, *Asteroids.* At the end of the grant, he co-authored (with D. Dunham) a second review paper dealing with the same topic for *Asteroids II.* Other occultation-related review papers by Millis appeared in the *Proceedings of IAU Symposium No. 118, Instrumentation and Research Programmes for Small Telescopes,* and in the *Solar System Photometry Handbook.*

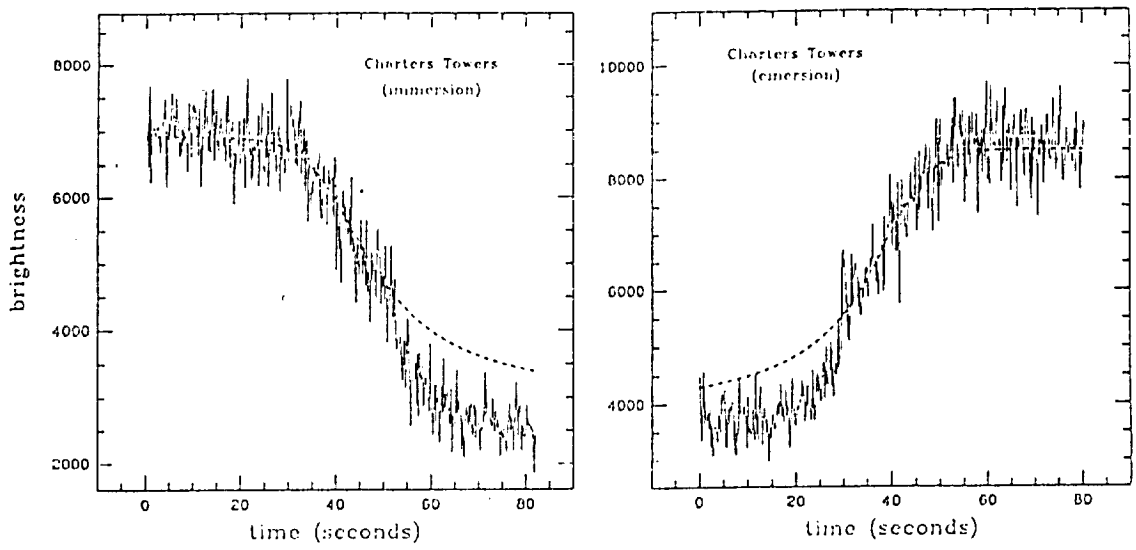

Figure 2. The immersion and emersion lightcurves recorded by the Lowell expedition to Charters Towers in northeastern Australia. Dashed curves represent isothermal model lightcurves fitted to the observations above the haze layer.

BIBLIOGRAPHY

The following papers were published with total or partial support from NSG-7603:

Bowell, E., and Wasserman, L. H. (1984). Predictions of occultations of stars by Comet Crommelin. *International Halley Watch Newsletter* No. 4, pp. 31–37.

Bowell, E., and Wasserman, L. H. (1984). Predictions of stars and radio sources. *International Halley Watch Newsletter* No. 5, pp. 72–87.

Bowell, E., and Wasserman, L. H. (1985). Predictions of occultations of stars by Comet Halley. *International Halley Watch Newsletter* No. 6, pp. 43–46.

Bowell, E., and Wasserman, L. H. (1985). Predictions of occultations of stars by Comet Giacobini–Zinner and prediction updates for Comet Halley. *International Halley Watch Newsletter* No. 7, pp. 30–37.

Bowell, E., Wasserman, L. H., Baum W. A., Millis, R. L., and Lumme, K. (1984). Occultations of stars and radio sources by comets: Predictions and observing prospects. In *Cometary Astrometry* (D. K. Yeomans, R. M. West, R. S. Harrington, and B. G. Marsden, eds.), pp. 105–122. Jet Propulsion Laboratory, Pasadena.

Bowell, E., Wasserman, L. H., and Millis, R. L. (1985). Stellar appulses by P/Halley, 1983 through 1987. *Bull. Am. Astron. Soc.* **15**, 804.

Dunham, D. W., Van Flandern, T. C., Millis, R. L., Chapman, C. R., Maley, P. D., and Povenmire, H. (1983). The size and shape of (2) Pallas from its occultation of 1 Vulpeculae on 1983 May 29. *Bull. Am. Astron. Soc.* **15**, 822.

Dunham, E., Baron, R. L., Elliot, J. L., Millis, R. L., Bowell, E., and Wasserman, L. H. (1980). Measuring the diameter of Juno. *Sky and Telescope* **59**, 276–278.

Elliot, J. L., Dunham, E. W., Bosch, A. S., Slivan, S. M., Young, L. A., Wasserman, L. H., and Millis, R. L. (1988). Stellar occultation observations of Pluto's atmosphere. *Bull. Am. Astron. Soc.* **20**, 805.

Elliot, J. L., Dunham, E. W., Bosch, A. S., Slivan, S. M., Young, L. A., Wasserman, L. H., and Millis, R. L. (1989). Pluto's atmosphere. *Icarus* **77**, 148–170.

Elliot, J. L., Mink, D. J., Elias, J. H., Liller, W., Nicholson, P. D., Jones, T. J., and Franz, O. G. (1981). No evidence of rings around Neptune. *Nature* **294**, 526–529.

Hubbard, W. B., Nicholson, P. D., Lellouch, E., Sicardy, B., Brahic, A., Vilas, F., Bochet, P., McLaren, R. A., Millis, R. L., Wasserman, L. H., Elias, J. H., Mathews, K., and Perrier, C. (1987). Oblateness, radius, and mean stratospheric temperature of Neptune from the 1985 August 20 occultation. *Icarus* **72**, 635–646.

Millis, R. L. (1980). Occultation of AGK3+0°1022 by (3) Juno. *IAU Circ.* No. 3444.

Millis, R. L. (1983). Occultations by (4) Vesta. *IAU Circ.* No. 3890.

Millis, R. L. (1983). Occultations by planets and satellites. In *Solar System Photometry Handbook* (R. M. Genet, ed.), pp. 7-1 through 7-18. Willman-Bell, Inc., Richmond.

Millis, R. L. (1983). *Astronomical Photometry* [a review]. *Icarus* **55**, 499.

Millis, R. L. (1986). Occultation studies with small telescopes. In *Instrumentation and Research Programmes for Small Telescopes*, IAU Symposium No. 118 (J. B. Hearnshaw and P. L. Cottrell, eds.), pp. 119–211. D. Reidel, Dordrecht.

Millis, R. L., Franz, O. G., Wasserman, L. H., and Bowell, E. (1983). Occultations of stars by solar system objects. III. A photographic search for occultations of faint stars by selected asteroids. *Astron. J.* **88**, 236–238.

Millis, R. L., and Wasserman, L. H. (1984). Occultations by Vesta. *Bull. Am. Astron. Soc.* **16**, 67.

Millis, R. L., Wasserman, L. H., Bowell, E., and Franz, O. G. (1980). The size and shape of Juno from its occultation of AGK3+0°1022. *Bull. Am. Astron. Soc.* **12**, 662.

Millis, R. L., Wasserman, L. H., Bowell, E., Franz, O. G., and Klemola, A. (1983). Asteroid occultations – progress and prospects. *Bull. Am. Astron. Soc.* **15**, 822.

Millis, R. L., Wasserman, L. H., Bowell, E., Franz, O. G., Klemola, A., and Dunham, D. W. (1984). The diameter of 375 Ursula from its occultation of AG+39°303. *Astron. J.* **89**, 592–596.

Millis, R. L., Wasserman, L. H., Bowell, E., Franz, O. G., Nye, R., Osborn, W., and Klemola, A. (1985). The occultation of AG+29°398 by 93 Minerva. *Icarus* **61**, 124–131.

Millis, R. L., Wasserman, L. H., Bowell, E., Franz, O. G., White, N. M., Lockwood, G. W. Nye, R., Bertram, R., Osborn, W., Klemola, A., Dunham, E., Baron, R. L., Elliot, J. L., Harris, A., Young, J. W., Faulkner, J., Stanton, R., Reitsema, H. J., Hubbard, W. B., Zellner, B., Lebofsky, L., Cruikshank, D. P., Macknik, L. S., Becklin, E. E., Morrison, D., Lonsdale, C. J., Kunkle, T. D., Lee, T., Gatley, I., A'Hearn, M. F., DuPuy, D. L., Nolthenius, R., Ford, H., McKenna, D., Placova, Z., Horne, K., Sandmann, W., Taylor, G. E., and Tucker, R. (1981). The diameter of Juno from its occultation of AG+0°1022. *Astron. J.* **86**, 306–313.

Millis, R. L., Wasserman, L. H., Bowell, E., Harris, A. W., Young, J. W., Barucci, M. A., Williamon, R. M., Manly, P. L., Dunham, D. W., Olson, R. W., Baggett, W. E., and Zeigler, K. W. (1989). The diameter, shape, albedo, and rotation of 47 Aglaja. *Icarus* **81**, 375–385.

Millis, R. L., Wasserman, L. H., Franz, O. G., and Bowell, E. (1982). The occultation diameter of 88 Thisbe. *Bull. Am. Astron. Soc.* **14**, 725.

Millis, R. L., Wasserman, L. H., Franz, O. G., Bowell, E., and Klemola, A. (1984). Occultations of stars by solar system objects. V. A photographic search for occultations by selected asteroids in 1984. *Astron. J.* **89**, 698–701.

Millis, R. L., Wasserman, L. H., Franz, O. G., Bowell, E., Nye, R. A., Thompson, D. T., White, N. M., Hubbard, W. B., Eplee, Jr., L. A., Lebofsky, L. A., Marcialis, R. L., Greenberg, R. J., Hunten, D. M., Reitsema, H. J., Qian Bochen, Maley, P. D., Klemola, A. R., and Yeomans, D. K. (1989). Observations of the 8 December 1987 occultation of AG +40°0783 by 324 Bamberga. *Astron. J.* **98**, 1094–1099.

Millis, R. L., Wasserman, L. H., Franz, O. G., Dahn, C. C., and Klemola, A. R. (1989). The mass ratio of the Pluto/Charon system. *EOS* **70**, 381.

Millis, R., Wasserman, L., Franz, O., Hubbard, W., Lebofsky, L., Goff, R., Marcialis, R., Sykes, M., Fecker, J., Hunten, D., Reitsema, H., Zellner, B., Rios, M., Dunham, E., Klavetter, J., Meech, K., Oswalt, T., Rafert, J., A'Hearn, M., Schneider, G., Osborn, W., Parker, D., Klemola, A., and Pirronen, J. (1985). The occultation diameter of Ceres. *Bull. Am. Astron. Soc.* **17**, 729.

Millis, R. L., Wasserman, L. H., Franz, O. G., Nye, R. A., Gilmore, A. C., Kilmartin, P. M., Allen, W. H., Watson, R. D., Dieters, S. W., Hill, K. M., Giles, A. B., Blow, G., Priestley, J., Walker, W. S. G., Marino, B. F., Dix, D. G., Page, A., Kennedy, H. D., Elliot, J. L., Dunham, E., Bosh, A. S., Young, L. A., Slivan, S. M., and Klemola, A. R. (1988). Observations of the 9 June 1988 occultation by Pluto. *Bull. Am. Astron. Soc.* **20**, 806.

Millis, R. L., Wasserman, L. H., Franz, O., Nye, R., Oliver, R., Jones, S., Kreidl, T., A'Hearn, M., Schnurr, R., and Osborn, W. (1985). Observations of the occultation of BD+8°471 by Ceres. *Publ. Astron. Soc. Pac.* **97**, 900.

Millis, R. L., Wasserman, L. H., Franz, O. G., Nye, R. A., Oliver, R. C., Kreidl, T. J., Jones, S. E., and 35 other authors (1987). The size, shape, density, and albedo of Ceres from its occultation of BD+8°471. *Icarus* **72**, 507–518.

Millis, R. L., Wasserman, L. H., Franz, O. G., White, N. M., Bowell, E., Klemola, A., Elliott, R. C., Smethells, W. G., Price, P. M., McKay, C. P., Steel, D. I., Everhart, E., and Everhart, E. M. (1983). The diameter of 88 Thisbe from its occultation of SAO 187124. *Astron. J.* **88**, 229–235.

Millis, R. L., Wasserman, L. H., and French, R. G. (1987). Observations of the 22 April 1982 stellar occultation by Uranus and the rings. *Icarus* **69**, 176–184.

Millis, R. L., Wasserman, L. H., Williamon, R. M., Dunham, D. W., Manly, P. L., Olson, R. W., Baggett, W. E., Maley, P. D., Zeigler, K. W., and Klemola, A. R. (1984). The occultation diameter of 47 Aglaja. *Bull. Am. Astron. Soc.* **16**, 1027.

Nye, R. A., Oliver, R. C., and Millis, R. L. (1982). A portable system for high-speed photometry of occultations. *Bull. Am. Astron. Soc.* **14**, 711.

Reitsema, H., Hubbard, W., Hunten, D., Porco, C., Brosch, N., Nevo, Y., Carreira, E., Rossi, R., and Wasserman, L. H. (1989). Preliminary results from the occultation of 28 Sgr by the Saturn system: Titan. *Bull. Am. Astron. Soc.* **21**, 959.

Wasserman, L. H., and Bowell, E. (1980). An efficient, automated method of finding asterod occultations of catalog stars. *Bull. Am. Astron. Soc.* **12**, 664.

Wasserman, L. H., and Bowell, E. (1985). Predicted occultations by Comets P/Giacobini-Zinner and P/Halley. *Publ. Astron. Soc. Pac.* **97**, 905.

Wasserman, L. H., and Bowell, E. (1986). Astrometry with the Lowell PDS. In *Astrometric Techniques, IAU Symposium No. 109* (H. K. Eichhorn and R. J. Leacock, eds.), pp. 231–136.

Wasserman, L. H., Bowell, E., and Millis, R. L. (1981). Occultations of stars by solar system objects. II. Occultations of catalog stars by asteroids in 1982 and 1983. *Astron. J.* **86**, 1974–1979.

Wasserman, L. H., Bowell, E., and Millis, R. L. (1983). Occultations of stars by solar system objects. IV. Occultations of catalog stars by asteroids in 1984 and 1985. *Astron. J.* **88**, 1670–1675.

Wasserman, L. H., Bowell, E., and Millis, R. L. (1985). Occultations of stars by solar system objects. VI. Occultations of catalog stars by asteroids in 1986 and 1987. *Astron. J.* **90**, 2124–2129.

Wasserman, L. H., Bowell, E., and Millis, R. L. (1987). Asteroid occultations in 1988 and 1989. *Bull. Am. Astron. Soc.* **19**, 824.

Wasserman, L. H., Bowell, E., and Millis, R. L. (1987). Occultations of catalog stars by asteroids in 1988 and 1989. *Astron. J.* **94**, 1364–1372.

Wasserman, L. H., and Millis, R. L. (1984). The 22 April 1982 occultation of star KME-14 by Uranus and its rings. *Bull. Am. Astron. Soc.* **16,** 660.

Wasserman, L. H., Millis, R. L., and Bowell, E. (1989). Predictions of occultations for 1990 and 1991. *Bull. Am. Astron. Soc.* **21,** 968.

Wasserman, L. H., Millis, R. L., and Bowell, E. (1990). Occultations of stars by solar system objects. VII. Occultations of catalog stars by asteroids, planets, Titan, and Triton in 1990 and 1991. *Astron. J.* **99,** 723–734.

Wasserman, L. H., Millis, R. L., Bowell, E., Franz, O. G., and Osborn, W. (1983). The occultation diameters of 375 Ursula and 93 Minerva. *Bull. Am. Astron. Soc.* **15,** 822.

Wasserman, L. H., Millis, R. L., and Franz, O. G. (1986). The occultation of AG+20°1138 by 129 Antigone on 11 April 1985. *Bull. Am. Astron. Soc.* **18,** 797.

Wasserman, L. H., Millis, R. L., Franz, O. G., A'Hearn, M. F., Osborn, W., and Klemola, A. (1986). The 13 November 1984 occultation of BD+08°0471 by (1) Ceres. In *Asteroids, Comets, Meteors II* (C.-I. Lagerkvist, B. A. Lindblad, H. Lundstedt, and H. Rickman, eds.), pp. 99–103. Uppsala University, Uppsala.

Wasserman, L. H., Millis, R. L., Franz, O. G., and Bowell, E. (1982). A photographic search for stars to be occulted by the larger asteroids in 1983. *Bull. Am. Astron. Soc.* **14,** 729.

Wasserman, L. H., Millis, R. L., Franz, O. G., Klemola, A. R., and Dahn, C. C. (1988). Precise astrometry of the Pluto/Charon system. *Bull. Am. Astron. Soc.* **20,** 806.